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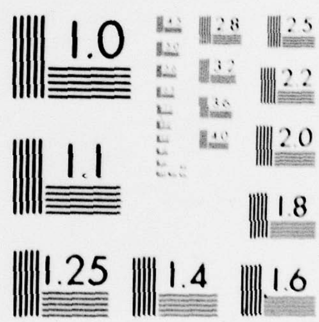

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An analysis of the launch tube environment produced by an aluminized rocket propellant was performed. Several matrix and liner materials were evaluated for their suitability for repeated use in launch tubes. Tubular specimens were fabricated and tested using a torch test fixture and a grit blast procedure. Twelve of the most promising systems were selected for shipment to the Army Missile Command for further evaluation.

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Technical Report
Contract No. DAAH01-76-C-0483
Reusability of Filament Wound Launch Tubes
Period: January 14, 1976-July 14, 1976

INTRODUCTION

The work covered in this report was performed under contract DAAH01-76-C-0483 and is for the contract period of January 14, 1976 through July 14, 1976.

Although high strength fiber/resin composites have been used extensively in rocket launch tubes by the Army and others, in these applications the launch tube has been a one shot, expendable item. An obvious improvement in the cost effectiveness of some launch tube applications could be achieved if the launch tubes could be reused.

The purpose of this study was to define several alternative material/design systems for filament wound launch tubes which have the potential to withstand repeated exposure to an environment caused by the aluminized propellant and to supply the Army Missile Command with tubular specimens of the most promising systems for further testing and evaluation.

DISCUSSION

ROCKET EXHAUST ENVIRONMENT

The inside of the launch tube is subjected to an environment that includes several potential forms of attack. Primarily, ablation of the launch tube surface is a result of thermal damage and mechanical abrasion. The thermal damage is a function of gas temperature, velocity and time of exposure. Mechanical abrasion is due to the particulate matter present in the combustion products of aluminized rocket propellant.

The relative significance and interaction of these two effects is difficult to predict analytically. However, in order to obtain an order of magnitude idea of the thermal environment in the launch tube, the following analysis based on available information was performed.

LAUNCH TUBE THERMAL ANALYSIS

In order to evaluate the performance of various launch tubes in combination with different rockets, it is necessary to determine approximate flame velocities and tube surface temperatures. Some assumptions were necessary to obtain these values which, in addition to uncertainties associated with empirical equations, limit the accuracy of the results. However, the analysis does give good comparative data and indicates what effects a variable has on tube performance.

A step-by-step analysis is performed for rocket #3 (per Technical Requirement No. 6005) in a 3-inch diameter launch tube. Results from a similar analysis are also given for rockets #1 and #2 (see Table I for characteristics of rockets #1 thru #3).

For rocket #3:

$P_o = 6150$ psi
$k = 1.18$
$T_o = 6310$ °R
$D_1 = 1.71$ in. (throat)
$D_2 = 2.50$ in. (nozzle)
$D_3 = 3.00$ in. (tube)

$g_c = 32.2 \dfrac{\text{ft-lb}_m}{\text{lb}_f \text{ sec}^2}$

$R = 64.4 \dfrac{\text{ft-lbf}}{\text{lbm}°\text{R}}$

Burntime = .008 sec.
$P_3 = 500$ psi (assumed)

Analysis of the exhaust gases of a typical polyurethane fuel containing aluminum yields the following bulk properties:

$C_p = 2.0$ Btu/lbm°F
$Pr = .69$
$\rho = .007$ lbm/ft^3
$\mu = 2.3 \times 10^{-5}$ lbm/ft-sec
$R = 64.4$ ft-lb$_f$/lb$_m$°R

For an isentropic flow process, the nozzle exit velocity can be found:

$$M_2 = M_1 A_1/A_2 \sqrt{\left(\frac{1 + \frac{k-1}{2} M_2^2}{1 + \frac{k-1}{2} M_1^2}\right)^{\left(\frac{k+1}{k-1}\right)}} = 2.1 \qquad (1)$$

The acoustic velocity at the nozzle was found:

$$V_a = \sqrt{g_c kRT} = 3330 \text{ ft/sec} \qquad (2)$$

which results in an exit velocity of

$$V_2 = 7000 \text{ ft/sec}$$

The pressure at the nozzle was:

$$P_2 = P_o \left(1 - V_2^2 \frac{k-1}{2gk} \frac{1}{RTo}\right)^{\left(\frac{k}{k-1}\right)} = 685 \qquad (3)$$

The existence of an additional pressure drop from the nozzle (P_2) to the tube (P_3) resulted in the assumption of a 500 psi tube pressure.

To find the gas temperature at the nozzle:

$$T_2 = T_o \left(\frac{P_2}{P_o}\right)^{\left(\frac{k-1}{k}\right)} = 4515\ ^\circ R \qquad (4)$$

Equations (2), (3) and (4) were solved successively to close in on the given solution.

To obtain the gas velocity in the tube, the principle of conservation of mass was applied.

$$V_3 = \frac{\rho_2}{\rho_3} \frac{A_2}{A_3} V_2 = 6300 \text{ ft/sec}$$

To find the gas temperature in the tube

$$T_3 = T_o \left(\frac{P_3}{P_o}\right)^{\left(\frac{k-1}{k}\right)} = 4300\ ^\circ R$$

The adiabatic wall temperature, which is the true driving potential, is not significantly lower than the temperature (T_3) calculated.

The following empirical equation was used to find the convection heat transfer coefficient.

$$h = .023\ R_e^{-.2}\ Pr^{-2/3}\ C_p\ \rho V = 340\ B_{tu}/\text{hr-ft}\ ^\circ F$$

Radiation heat transfer was analyzed and found to be negligible.

Using the calculated values for T_3 and h and assuming appropriate material properties for the launch tube, the approximate tube wall temperature after .008 seconds was determined to be 550°F.

A summary of the results of the analysis of the three rocket systems listed in Technical Requirement No. 6005 is given in Table I.

TABLE I

GIVEN:	ROCKET #1	ROCKET #2	ROCKET #3
P_o	2500	2200	6150 psi
k	1.21	1.20	1.18
T_o	5740	5350	6310 °R
D_1	1.8	1.96	1.71 in.
D_2	5.8	3.11	2.5 in.
D_3	8	14	3 in.
Burn Time	.25	.30	.008 sec.
g	32.2	32.2	32.2 ft-lb$_m$/lb$_f$ sec^2
R	64.4	64.4	64.4 ft-lb$_f$/lb$_m$ °R
Assume:			
P_3	20	50	500 psi
Results:			
V_2	8600	6700	7000 ft/sec
V_3	7400	1000	6300 ft/sec
h	640	115	340 Btu/hr-ft °F
T_3	2400	2850	4300 °R
T_{wall}	1550	1050	550°F

SUBSCRIPTS

o - chamber
1 - throat
2 - nozzle
3 - tube

From the results of the thermal analysis it would appear that thermal damage should be less significant for high impulse, short burn time rocket systems than for the larger, slower systems. For most resin systems considered in this study, brief exposure to 500-600°F should not result in any permanent damage. The Epon 828/NMA resin system, for example, is sometimes post cured at near 500°F to increase its heat distorsion temperature. Examination of launch tubes which have been subjected to an exhaust environment similar to rocket No. 3 indicates no obvious evidence of thermal damage (i.e., charring or discoloration). Laboratory tests were run by Brunswick on tubes of similar construction, and the surface condition of the fired tubes could only be duplicated by alumina grit blasting. Torch tests on these tubes and others, reported on in more detail later in this report, resulted in discoloration, blistering and, finally, charring of the resin, none of which was apparent on the fired launch tubes. Photographs of a fired launch tube and tube sections subjected to laboratory tests are included as an appendix to this report.

It is possible that heat softening may have contributed to the erosion in the fired tubes, and that some amount of surface sublimation may be taking place, and it is likely that in rocket systems similar to no's. 1 and 2 in the Technical Requirements the thermal effects would be significant. However, these analytical and experimental results do raise some questions about the validity of a pure thermal test for the evaluation of launch tube materials in some applications.

MATERIAL SYSTEM SELECTION

As part of the original program plan, a matrix of potential materials for winding and liners was generated. This matrix is given as Table II. As the program progressed, the original matrix was continuously revised and expanded. Two general approaches were considered. The first and preferred approach was to define a winding resin which would result in a composite which met the program objectives. As an alternative approach, a liner material to shield the overwrap from the rocket exhaust environment was considered.

The criteria for selecting resin systems for winding was based on the consideration of heat distortion, flammability and toughness (abrasion resistance) as well as cost and processability.

From preliminary results obtained at MICOM on 2.75 inch diameter launch tubes, it appeared that a thin (approx. .020") gel coat liner offered a considerable amount of protection to the tube surface, and liner material evaluation was a significant part of this study. Included in the criteria for liner material selection was: heat distortion temperature, flammability, abrasion resistance, thermal conductivity and auto-lubrication. Increased thermal conductivity of the liner material would increase the thermal capacity, and thus reduce the surface temperature of the tube, while auto-lubrication (e.g., graphite) may reduce abrasion.

A summary of the matrix and liner materials evaluated in this study is given in Table III. The alphabetic code was assigned to facilitate tabulation of test data.

TABLE II

REUSABLE LAUNCH TUBE MATERIAL MATRIX - CC 10211 (1)

SYSTEM NO.	MATRIX MATERIAL	LINER CONFIG./MAT'L.	RESISTANT TO: HEAT	WEAR	COMMENTS
1	LRF-092	None			Baseline (250°F)
2	LRF-216	None			Low HDT (150°F)
3	APCO 2447	None	X		High HDT (350°F)
4	Kerimid	None	X		High Temp. Resins
5	Triazine A	None	X		High Temp. Resins
6	XYLOC (235C)	None	X		High Temp. Resins
7	LRF-092	LRF-002/Cabosil			Liner Effects
8	LRF-092	LRF-002/Asbestos			Liner Effects
9	LRF-092	LRF-002/Graphite Cloth	X	X	Graphite for Therm. Cond. & Wear
10	LRF-092	APCO 2447/Cabosil	X		Novolac Epoxy Liner
11	LRF-092	APCO 2447/Asbestos	X		Novolac Epoxy Liner
12	LRF-092	APCO 2447/Graphite Cloth	X	X	Novolac Epoxy Liner
13	LRF-092	LRF-092/Barrium-MICA		X	Already wound at Amerac
14	LRF-092	$AlPO_4$	X		High Temp. (1200°F)
15	LRF-092	$Al(OH)_3$ H_2O/Resin (?)	X		Emits H_2O When Heated
16	LRF-092	Epoxy/Urethane		X	Tough
17	LRF-092	Silicone Elastomer (RTV)	X	X	Tough & High Temp.
18	APCO 2447	"Coors Ceramic Particles"	X	X	Suggested by T.T. Chiao
19	LRF-092	Longo Mat/Resin (?)		X	Fiber Direction
20	LRF-092	Veil Mat/Resin (?)			Liner Effects

(1) This list will be periodically updated as new information is received. Tubes are to be shipped from 12 systems.

TABLE III
SUMMARY OF MATERIAL SYSTEMS EVALUATED

MATERIAL CODE	MATERIAL DESCRIPTION
Matrix Materials	
A	Epon 828/Nadic Methyl Anhydride/Benzyldimethyl Amine
B	Epon 828/Nadic Methyl Anhydride/ATC-3
C	Apco 2447 (Novolac Epoxy)
D	Dow 7575.02 (CTBN Modified Epoxy)
E	Epon 828/NMA (Tube Provided by MICOM)
F	Xyloc 235-C
Liner Materials	
G	Epon 828/Aliphatic Amine/Cabosil
H	Epon 828/Aliphatic Amine/Asbestos Cloth
I	Epon 828/Aliphatic Amine/Chopped Graphite
J	Resin C/Cabosil
K	Resin C/Asbestos Cloth
L	Resin C/Chopped Graphite
M	Resin A/Graphite Cloth
N	Resin C/Graphite Cloth
O	Polane (Polyurethane)
P	Resin A/Cabosil
Q	Resin D/Cabosil
R	Barium-Mica (Supplied by MICOM)

TUBE PROCESSING

Tube specimens in this study were fabricated to detailed processing documents. The tube overwraps were all wound with 20 end, Type 801 E-glass at ± 70° wind angle and 14 rovings per inch. Four layers were applied to an approximate thickness of .040 inch. An attempt was made to hold the liner thickness to around .020 inch, but the actual thickness varied depending on the nature of the liner material. The more viscous materials tended to result in thicker liners. In all cases an uncured gel coat was applied to the mandrel surface prior to winding to eliminate dry fibers from the inner tube surface and to improve the bond between the liner and the overwrap for the lined tubes.

EXPERIMENTAL EVALUATION

Most of the test work was carried out using the same 3.110 inch diameter tubes which were eventually shipped to MICOM for further evaluation. A few materials were subjected to preliminary evaluation using flat laminates and NOL rings, but the ones selected for shipment to MICOM were also evaluated as tubular specimens. A summary of tubes shipped to MICOM is given in Table IV. Several other resin systems were considered, but because of various processing impracticalities and cost disadvantages, they were not selected for experimental evaluation.

Evaluation of each material system was performed using the test fixture shown in Figure 1. The fixture was designed to pass the specimen through a controlled thermal or abrasive environment produced by an oxyacetylene torch or a grit blast nozzle. In Figure 2 is a photograph of the test fixture in operation. The grit used in this test was 100 mesh alumina. The test specimen can be passed through the environment at varying speeds by means of a DC motor and variable power supply. After two combined torch and grit blast tests using the fixture, it was decided that the abrasive environment was too severe for the fixture and all further grit blast tests were run using a hand held gun and a fixed period of exposure.

Hardness of the specimens was measured using a hand held Barcol Impressor, Model 934-1. Ablation was measured by measuring the specimen thickness before and after testing. Some difficulty was encountered in measuring specimen thickness. Because irregularities in the outside surface were occasionally of the same order of magnitude as the ablation being measured, accurate measurements were not always possible.

RESULTS

A summary of the results of the torch tests and grit blast tests is presented in Table V. For every specimen the amount of ablation (thickness reduction) was measured, and a Barcol Hardness test was performed before and after each torch test. In addition, pictures were taken of each of the specimens and are included in Appendix A.

TABLE IV
SUMMARY OF LAUNCH TUBE SPECIMENS SHIPPED TO MICOM

S/N	MATRIX	LINER MATERIAL
002	Epon 828 Ciba 906 Hardener (NMA) ATC-3 Accelerator	None
003	Apco 2447	None
006	Epon 828 Ciba 906 Hardener (NMA) BDMA	Chopped Graphite Fiber Epon 828 Aliphatic Amine
012	Dow XD-7818 Dow XD-7575.02 Epoxide 8 Tonox 6040	None
013	Epon 828 Ciba 906 Hardener (NMA) BDMA	Polane (Urethane)
014	Epon 828 Ciba 906 Hardener (NMA) BDMA	Epon 828 Ciba 906 Hardener (NMA) BDMA Filler (Cabosil)
015 (Baseline)	Epon 828 Ciba 906 Hardener (NMA) BDMA	None
017	Epon 828 Ciba 906 Hardener (NMA) BDMA	Dow XD-7575.02 Dow XD-7818 Epoxide 8 Tonox 6040
019	Xyloc 235 (Proprietary High Temperature Resin)	None
020	Epon 828 Ciba 906 Hardener (NMA) BDMA	Apco 2447 Chopped Graphite Roving
021	Epon 828 Ciba 906 Hardener (NMA) BDMA	Epon 828 Ciba 906 Hardener (NMA) ATC-3 Accelerator Cabosil
022	Epon 828 Ciba 906 Hardener (NMA) BDMA	Apco 2447 Cabosil

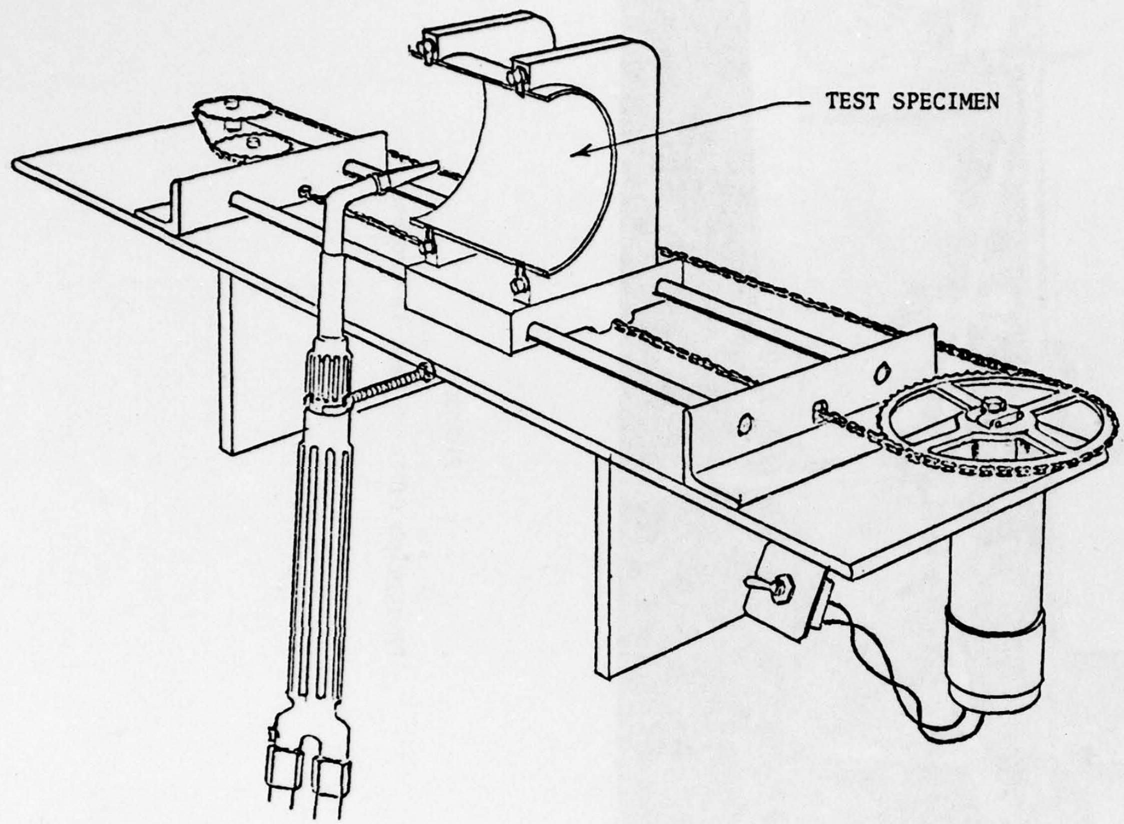

FIGURE 1
SKETCH OF TEST FIXTURE WITH TORCH MOUNTED

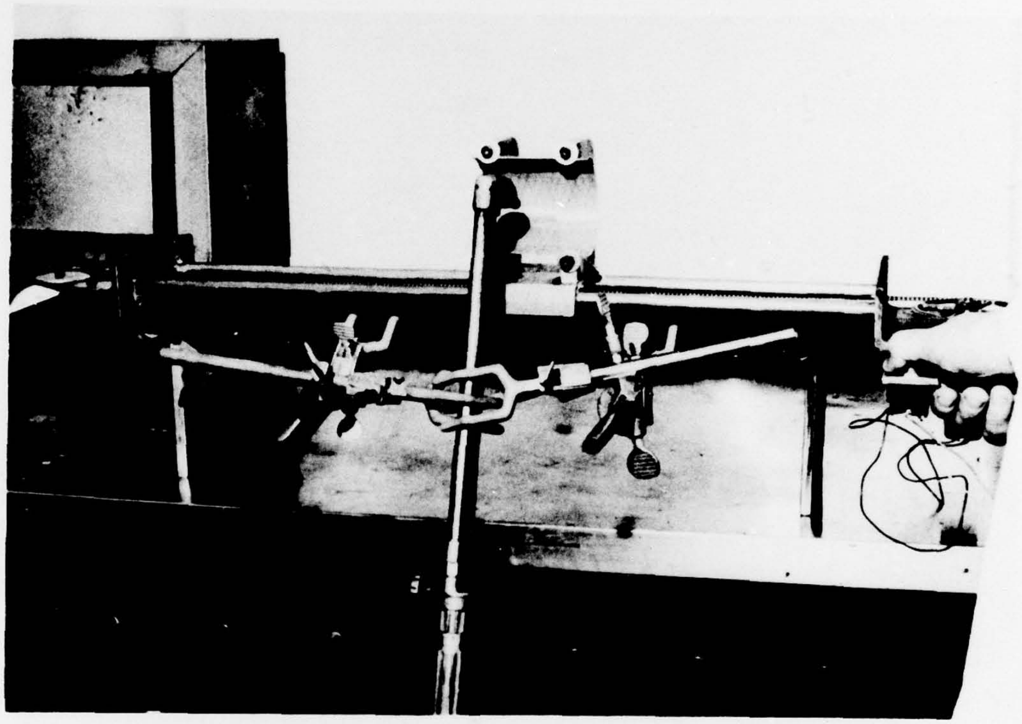

FIGURE 2

Photograph of Torch Test in Process

TABLE V(a) - TEST RESULTS

TUBE S/N	MATRIX	LINER	TEST TYPE	ABLATION (THICKNESS REDUCTION)	BARCOL HARDNESS BEFORE TEST	BARCOL HARDNESS AFTER TEST	OBSERVATIONS
001	A	-	Torch	.001"	73	64	Darkening, slight blistering
001	A	-	Torch	.000"	74	66	
001	A	-	Torch	.000"	73	66	
001	A	-	Grit	.006"	--	--	Resin ablated into first fiber layer
002	B	-	Torch	.001"	70	59	Darkening, slight blistering
002	B	-	Torch	.001"	65	60	
003	C	-	Torch	.001"	72	68	Slight blistering of surface
003	C	-	Torch	.001"	72	68	
003	C	-	Grit	.008"	--	--	Surface resin and part of 1st fiber layer ablated
004	A	G	Torch	(.005")	62	52	Slight darkening - no blisters
004	A	G	Torch & Grit	.007"	58	65	Liner and some fiber ablated
005	A	H	Torch	.003"	55	34	Darkening, slight ablation
005	A	H	Torch & Grit	.002"	55	42	Surface ablated - cloth fibers exposed
006	A	I	Torch	.000"	63	59	Slight darkening
006	A	I	Grit	.004"	--	--	Dulled surface, no fibers exposed
007	A	J	Torch	(.001")	69	70	Considerable darkening of surface, no blisters
007	A	J	Torch	(.001")	70	66	
007	A	J	Grit	.001"	--	--	Dull surface, no exposed fibers
008	A	K	Torch	.000"	57	57	Darkening and pitting of surface
008	A	K	Grit	.008"	--	--	Surface ablated - cloth fibers exposed

TABLE V(b) - TEST RESULTS

TUBE S/N	MATRIX	LINER	TEST TYPE	ABLATION (THICKNESS REDUCTION)	BARCOL HARDNESS BEFORE TEST	BARCOL HARDNESS AFTER TEST	OBSERVATIONS
009	A	L	Torch	.001"	70	66	Considerable darkening of surface, no blisters.
009	A	L	Grit	.002"	--	--	Dull surface, no exposed fibers.
010	A	M	Torch	.000"	64	62	Some damage where cloth came near surface.
010	A	M	Grit	.005"	--	--	Surface ablated to cloth.
011	A	N	Torch	.002"	68	69	Surface cracks & blisters corresponding to weave of cloth.
011	A	N	Torch	(.001")	69	60	Surface cracks & blisters corresponding to weave of cloth.
011	A	N	Grit	.013"	--	--	Resin ablated into the weave of the cloth.
012	D	-	Torch	(.001")	42	35	Surface blistering.
012	D	-	Grit	.010"	--	--	Ablation into 2nd ply of fibers.
013	A	O	Torch	.003"	58	64	Surface dull - possible charring.
013	A	O	Grit	.000"	--	--	Dulled surface.
014	A	P	Torch	.000"	53	52	Surface darkened.
014	A	P	Grit	.001"	--	--	Dulling of surface.
017	A	Q	Torch	.000"	53	52	
017	A	Q	Grit	.000"	--	--	
018	E	R	Torch	.000"	68	70	Slight surface darkening.
018	E	R	Grit	.007"	--	--	Liner ablated to 1st fiber ply.
019	F	-	Torch	.002"	50	42	Blisters formed under 1st fiber ply.
019	F	-	Grit	.004"	--	--	Ablation into first fiber ply.

The baseline tube as defined by MICOM was Type 801, E-glass with Shell Chemical Company's Epon 828. The accelerator/hardener system used with 828 for the baseline tube was methylnadic anhydride/benzyldimethyl-amine. To calibrate the effects of the torch test, two other "baseline" resin systems were evaluated - one with a higher heat distortion temperature (Apco 2447 Novolac Epoxy) and one with a lower heat distortion temperature (Epon 828 and methylnadic anhydride/ATC-3). The results of torch tests on these three systems without liners are given below.

	H.D.T.	ABLATION (REDUCTION IN THICKNESS)	HARDNESS BEFORE	HARDNESS AFTER
(2) Epon 828/ATC-3/NMA	150°F.	.001	67.5	59.5
(3) Epon 828/BDMA/NMA	250°F.	.000	73.3	65.2
(2) Apco 2447	350°F.	.001	72.0	68.0

All tests were performed with the nozzle 2" from the specimen and the specimen moving through the flame at 1.3 feet/second. The numbers in parenthesese indicate the number of specimens tested at this condition. There was very little scatter of these data (see Table IV). Although the results do not show ablation to be significant for any of the resin systems under these test conditions, there is an indication of a reduction in surface hardness. As might be expected, the higher heat distortion temperature resin system showed the smallest decrease in hardness.

MATRIX MATERIAL EVALUATION

As noted in Table II, several resin systems were considered for evaluation as a matrix material. The final selection of four (not including the baseline resin system) was based on a preliminary screening evaluation which considered processability and cost as well as performance potential. A brief discussion of those systems eliminated from consideration under this program and the reasons for their elimination follows.

Triazine A - Triazine is a high temperature resin system made by Mobay Chemical Co. Several resin castings and NOL rings were fabricated with this material but because of excessively high cure shrinkage and processing difficulties, it was deemed unsuitable for filament winding.

Polyimide - Polyimides show some amount of future promise for use in filament winding. They have the inherent disadvantages of high cost and a vacuum bag cure requirement. However, Brunswick has an active in-house program underway to investigate polyimides for filament winding, and it is possible that processing techniques may be developed which will make polyimides more practical for high volume filament wound parts.

Aluminum Phosphate - $AlPO_4$ is an inorganic material for which Brunswick has developed a process for use in high temperature, glass reinforced radomes. It was considered for launch tubes because of its high temperature resistance (approx. 1200°F), but because of its relatively complicated processing requirements and low abrasion resistance, it was eliminated as a viable candidate.

Of the four resin systems chosen for further evaluation as a matrix material, two were high temperature systems and one was an abrasion resistant (toughened) epoxy. The fourth was another anhydride cured Epon 828 system included as a comparison with the baseline system.

Apco 2447 Novolac Epoxy - This resin system appears to offer the best potential for high temperature (500°F) filament wound applications. It is a relatively high strength system that is easily adapted to filament winding. Results of the torch test indicated only a slight reduction in hardness after exposure to the flame.

High temperature strength retention test data developed by Brunswick is given below which indicates that at 550°F, there is only a 34% loss in tensile strength.

APCO 2447 NOVOLAC RESIN TENSILE STRENGTH

	ROOM TEMP.	350°F.	400°F.	450°F.	500°F.	550°F.
Stress	47,000 psi	38,000 psi	34,000 psi	33,000 psi	30,500 psi	31,000 psi
Std. Dev.	2,550 psi	2,926 psi	3,304 psi	2,002 psi	2,022 psi	2,371 psi
C.V.	5%	8%	10%	6%	7%	8%

Visual examination of the specimen following the torch test indicated that considerable darkening of the resin had taken place. However, because of the high temperature performance and processability of this resin, further consideration of Novolac epoxies is warranted.

Xyloc 235C - Xyloc is manufactured by Ciba Geigy for high temperature (to at least 400°F) applications. It must be vacuum bag cured and difficulty was encountered in maintaining resin content due to a significant decrease in viscosity at elevated cure temperatures. The specimen did not perform well under grit or torch testing. This may have been due, in part, to the low resin content. Grit blasting resulted in the errosion of the matrix well into the first fiber layer. Torch tests resulted in discoloration, blistering, and a reduction in surface hardness. Improved processing techniques must be defined before this system can be considered for launch tube applications.

Carboxyl Terminated Butadiene Acrylonitrile (CTBN) Modified Epoxy Resin - CTBN modified resin systems are recommended where a toughened fracture resistant matrix is desired. During cure of the epoxy small elastomeric particles precipitate out and act as crack arrestors in the matrix. It was felt that if abrasion were the primary form of attack, then this "toughened" material might be attractive. The effect of grit blasting on the CTBN matrix was surprisingly severe. The composite was eroded through the first ply of fiber (.010 inch). The thermal test results were darkening of the resin and a reduction in hardness.

Epon 828/NMA/ATC-3 - This is a relatively low heat distortion anhydride cured system. Its performance in the tests was similar to the baseline system.

Based on these bench test results, none of the matrix materials evaluated under this program offer any significant improvement over the baseline material. However, it must be emphasized that these bench tests do not duplicate rocket exhaust environments present in actual launch tubes, and a material should not be eliminated because of these test results alone.

LINER MATERIAL EVALUATION

The function of a polymeric liner in a launch tube is not entirely clear. From results obtained at MICOM and Brunswick on actual launch tubes, it appears that a relatively thin layer of resin on the inside of the tube provides considerable protection to the overwrap. In fact, it has been demonstrated that a tube with a liner of a material with a lower heat distortion temperature than the matrix material will perform better than the same tube without the liner. Three mechanisms were considered as potential functions of the liner. From a thermal standpoint, the liner may be providing a higher specific heat surface, thus reducing the surface temperature. The homgeneity of the liner may also make it less sensitive to thermal shock than a composite surface. Protection from abrasion may be provided due to the lower modulus of the liner as compared to the composite. The consideration of these mechanisms dictated the choice of materials evaluated under this portion of the program.

Each liner material will be briefly discussed including the results of testing.

Epon 828/Aliphatic Amine/Cabosil - This is a room temperature cure resin system and is similar to the TETA cured system tested by MICOM. The MICOM test results indicated that this liner suffered no apparent damage when subjected to rocket firing. Under the torch test, there was discoloration, and a reduction in hardness from 62 to 52. The apparent increase in specimen thickness may have been due to the difficulty in obtaining accurate thickness measurements. A combined torch and grit blast test was run on this material which resulted in .007 inch ablation and a net increase in hardness, probably indicating that much of the liner was blown away and the hardness measurement was being effected by the overwrap. This test is obviously more severe than MICOM's rocket firing. The appearance of the ablated surface was similar to the unlined launch tube tested at MICOM.

Epon 828/Aliphatic Amine/Asbestos tape - Asbestos tape has been occasionally used as a shield for composite structures in regions where high temperature rocket exhaust impinges directly on the surface. In most launch tubes the use of asbestos could probably be limited to the aft portion of the tube where thermal exposure is greatest. Exposure of the specimen to the torch test resulted in a small amount of measured ablation (.003 inch) and a significant reduction in surface hardness. A combination torch and grit blast test resulted in considerable ablation, exposing the asbestos fibers. The low cure temperature and relatively low strength of the resin system were probably detrimental under these test conditions.

Epon 828/Aliphatic Amine/Chopped Graphite - The degree to which a surface can absorb heat while minimizing wall temperature is determined by the specific heat and thermal conductivity of the wall material. Most resin systems are characterized by reasonably high specific heats but very low thermal conductivity. High conductivity fillers can be introduced into the resin to increase conductivity. For this study chopped graphite fibers were blended in the resin (8% by weight). In addition to improved conductivity, it was felt that the graphite may offer some surface lubrication in actual launch tubes. Results of the torch test indicated a possible improvement in hardness reduction (63 to 59 compared to 62 to 52 for no graphite). Grit blasting resulted in a dulling of the surface and .004" ablation but the liner was still intact.

Apco 2447/Cabosil - Because of its better high temperature strength, Apco 2447 was considered as a liner material. The torch test, again, resulted in considerable darkening of the surface with little hardness reduction. Two specimens from the same tube were torch tested with differing results, suggesting that the effect of the torch test on Apco 2447 may be somewhat irratic.

Apco 2447/Asbestos Cloth - The addition of asbestos cloth to the Apco 2447 liner appears to be detrimental to the liner's performance. Besides the usual darkening, the surface was badly ablated and marked with small pits. The pitting suggests that the surface may be subjected to thermal shock. These results are consistant with other asbestos cloth tests and, to some extent, with graphite cloth. It appears that a high resin content in the liner is a requirement.

Apco 2447/Chopped Graphite - The results from a chopped graphite filled Apco 2447 liner were similar to previous results using chopped graphite. The torch test resulted in a darkened surface and the grit blast in a dulled surface. There was little, if any, ablation.

Epon 828/Nadic Methyl Anhydride/Benzyldimethyl Amine/graphite cloth - In the original program definition, it was felt that a graphite cloth liner, besides providing the benefits of chopped graphite, would provide some additional reinforcement for the tube. Torch test of the specimen resulted in some localized surface damage where the weave of the cloth neared the surface of the resin. Grit blasting removed the thin layer of resin covering the cloth and exposed the graphite yarn. These results reiterate the need for a high resin content liner.

Apco 2447/Graphite cloth - The results of a Apco 2447/graphite cloth liner were similar to the Epon 828 system discussed above. Irratic hardness data was due to the irregular surface of the ablated cloth.

Polane (Sprayable Polyurethane) - If abrasion is a significant problem in launch tubes, then it follows that a tough elastomer might make a good liner material. A tube was fabricated by applying a sprayable urethane to a mold released mandrel and overwrapping with the baseline tube. The only effect of grit blasting was a dulling of the surface. The torch test darkened the surface to the point of charring. A urethane with higher temperature capability should be considered for future studies.

Epon 828/Nadic Methyl Anhydride/Benzyldimethyl Amine/Cabosil - As an additional experimental control, the baseline Epon 828 resin system with Cabosil was evaluated as a liner material and performed well. The only effect of the torch test was a slight darkening of the resin. The grit test dulled the surface slightly but resulted in no significant ablation.

CTBN Modified Epoxy/Cabosil - Because of its alleged toughness, CTBN modified epoxy was considered as a liner material. The torch test resulted in a darkening of the surface but no significant effect on hardness. The grit test, once again, dulled the surface with no measurable ablation.

Barium-Mica/Epoxy - This tube was not wound by Brunswick but provided by MICOM for evaluation. The Barium-Mica filler was an attempt to make the tube surface less sensitive to rocket exhaust. The liner in the tube provided was very thin (a few thousandths) and did not provide protection from grit ablation. Grit blasting exposed the first fiber layer. The torch test resulted in very little discoloration of the resin, but some light areas indicated the possibility of subsurface delamination. A thicker liner of this type may be worth further consideration.

CONCLUSIONS

Thermal analysis results indicate that at least some rocket launch tubes may be adaptable to an all composite design. The wall temperature associated with high impulse, low burn time rocket systems appears to be low enough (approx. 550°F) to allow the use of an epoxy on the inside diameter, however slower, long burn time systems may require some extra protection in the aft end of the launch tube to survive repeated firings.

From the results of the screening tests, it appears that a liner material is necessary to achieve the goal of reusability. Although the tests performed are qualitative in nature, based on these results, a high temperature matrix material alone does not show much promise of success. In addition, processing and cost disadvantages of most of these high temperature systems make them impractical for high production rate filament winding.

The tests performed for this study did not sufficiently discriminate between liner materials to allow final specific recommendations to be made. However, from test results and intuition, it appears that a relatively good strength retention under exposure to heat combined with abrasion resistance is the prime requirement of a liner material. Of the liner materials investigated, Apco 2447 and Epon 828/NMA with or without fillers (chopped graphite or Barium-Mica) seemed to offer the best potential for further investigation.

The use of fabric materials (i.e., asbestos tape and graphite cloth) in a liner was detrimental to the liner function. It appears that a high resin content layer of several thousandths of an inch in thickness is necessary to provide adequate protection to the tube surface.

Filler material such as graphite and barium-mica may offer advantages but a more discriminating test, such as an actual rocket firing, is necessary to fully evaluate their effect.

RECOMMENDATIONS

Results of this study indicate that reusable composite launch tubes are definitely a possibility. The experimental results point out the difficulty in simulating a rocket exhaust environment in the laboratory. It is recommended that this work be continued, using actual rocket motors as the test vehicle. Emphasis for future work should be placed on liner materials, with increased consideration of manufacturing techniques. In addition, some consideration should be given to the overwrap design. Optimization of the wind pattern is not only important from a strength consideration, but low angle (near longitudinal) fibers on the inside may be more resistant to abrasion from the rocket blast.

Using the results of this study (including MICOM test results) as a starting point, the follow-on program should allow for an iterative selection of materials and designs. If possible, experimental evaluation (rocket motor tests) should be carried out concurrently with material/design selection, so that the selection process can reflect prior results.

For maximum results, it is recommended that this follow-on study consider only material/design systems which use established processing techniques. A parallel, but separate, program could be undertaken which considers a more exotic material requiring a more extensive process development effort, such as polyimides. This would allow the main investigation to proceed undiluted by materials requiring an inordinate amount of time and effort.

More specific recommendations can be made when the results of the tests performed at MICOM are available for review. The MICOM tests and evaluation are somewhat different from those reported here and should provide additional information on the relative merits of the various material systems.

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Principles of Heat Transfer, F. Kreith

Handbook of Heat Transfer, Rohsenow & Hartrett

Rocket Propulsion Elements, 2nd Edition, G. Sutton

Handbook of Tables for Applied Engineering Science, CRC

LIST OF SYMBOLS

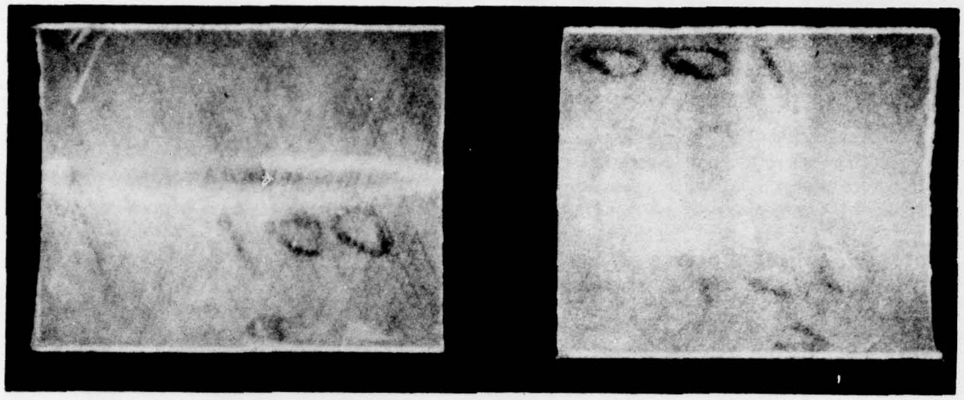
A	Cross Sectional Area of Flow
C_p	Specific Heat
D	Diameter
k	Specific Heat Ratio
M	Mach Number
P	Pressure
Pr	Prandtl Number
R	Gas Constant
h	Convection Heat Transfer Coefficient
V	Gas Velocity
ρ	Density
μ	Viscosity

SUBSCRIPTS

0	Pertaining to the Rocket Chamber
1	Pertaining to the Rocket Throat
2	Pertaining to the Nozzle Exit
3	Pertaining to the Launch Tube

APPENDIX

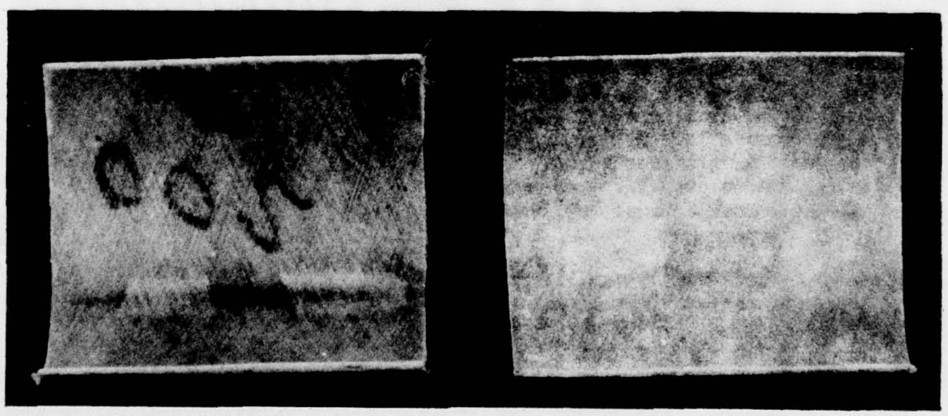
PHOTOGRAPHS OF TESTED SPECIMENS



Torch Test
S/N 001

Matrix: A

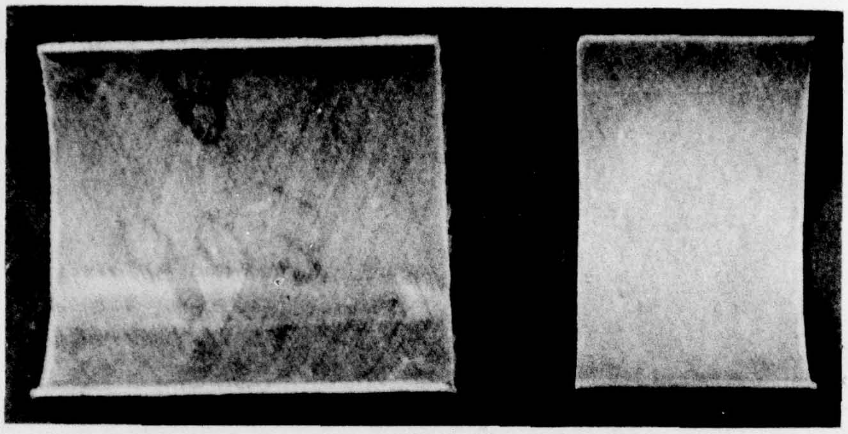
Grit Blast Test
Liner: None



Torch Test
S/N 002

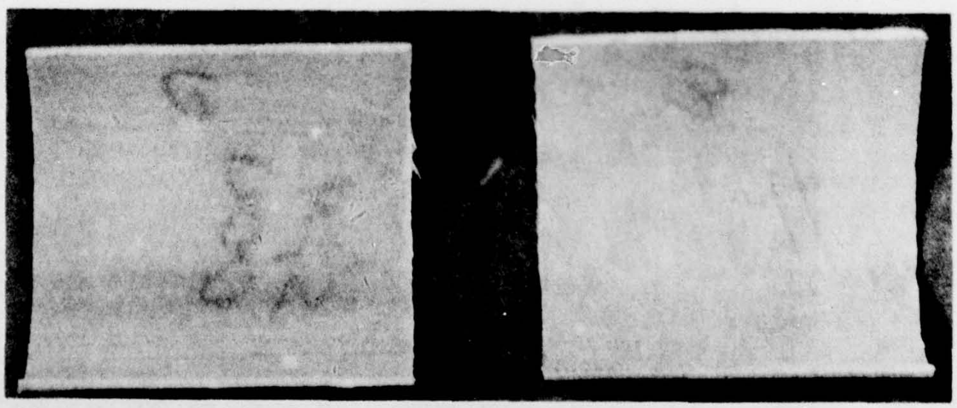
Matrix: B

Grit Blast Test
Liner: None



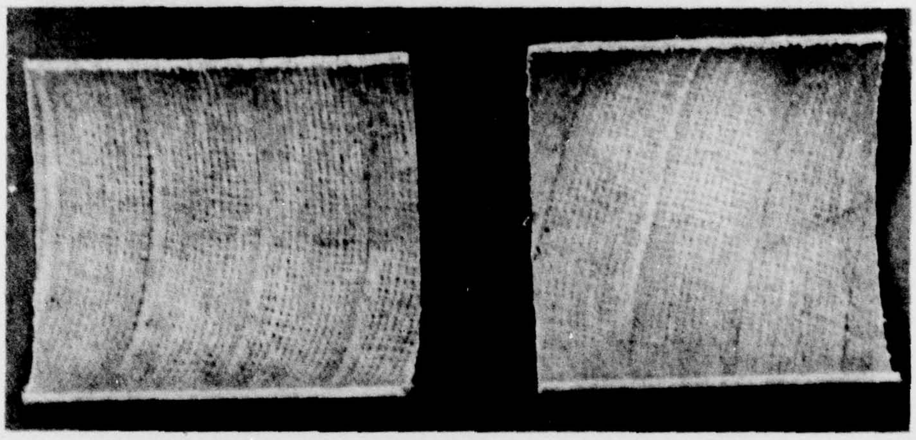
Torch Test
S/N 003 Matrix: C

Grit Blast Test
Liner: None



Torch Test
S/N 004 Matrix: A

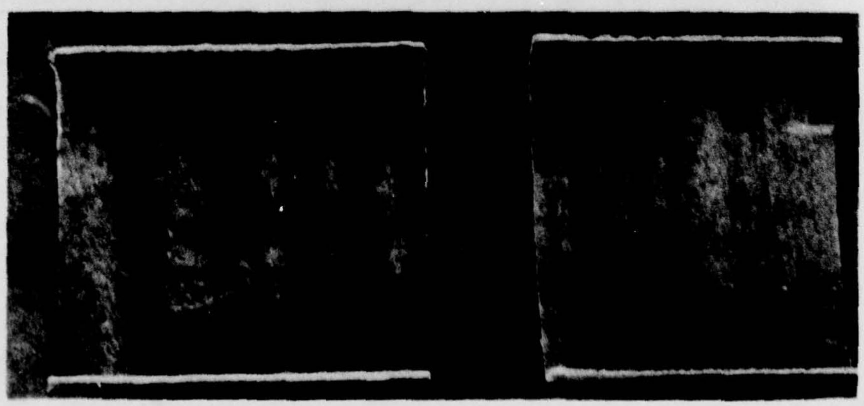
Torch/Grit Test
Liner: G



Torch Test
S/N 005

Matrix: A

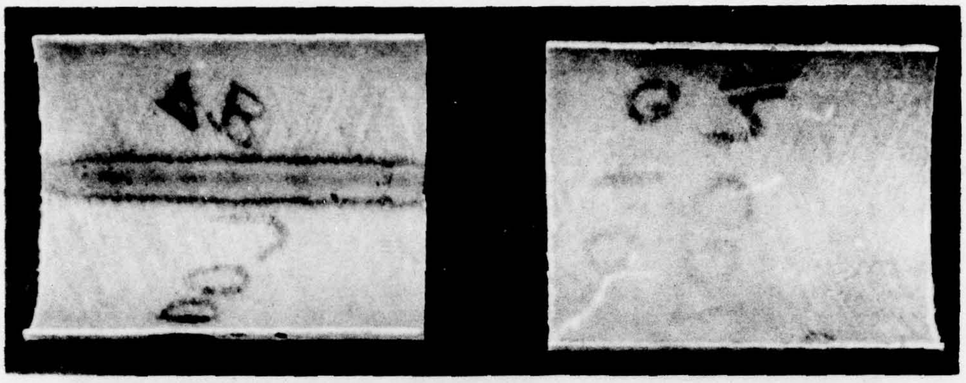
Torch/Grit Test
Liner: H



Torch Test
S/N 006

Matrix: A

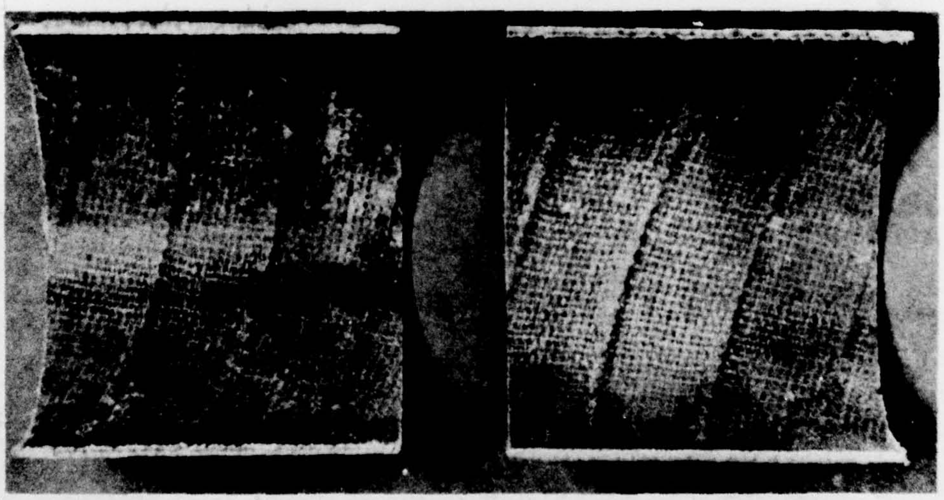
Grit Blast Test
Liner: I



Torch Test
S/N 007

Matrix: A

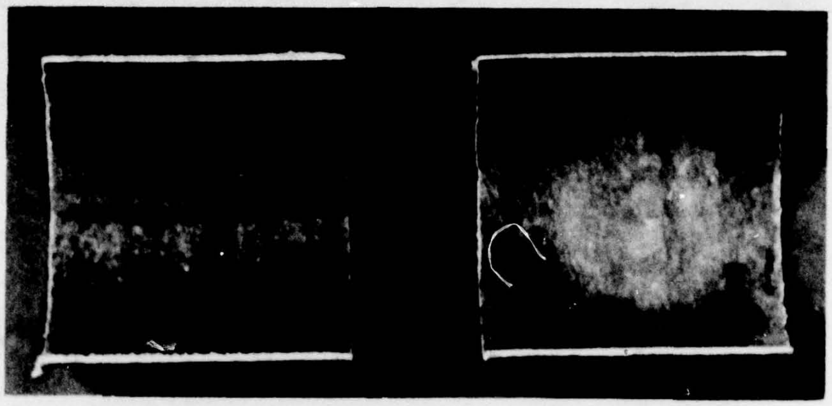
Grit Blast Test
Liner: J



Torch Test
S/N 008

Matrix: A

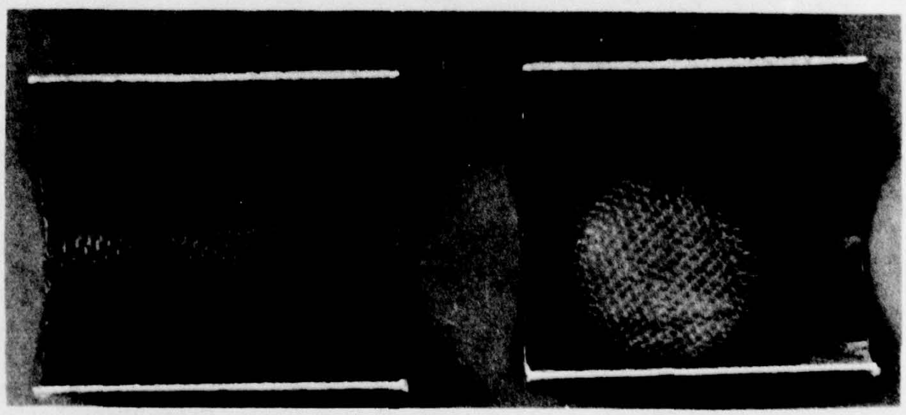
Grit Blast Test
Liner: K



Torch Test
S/N 009

Matrix: A

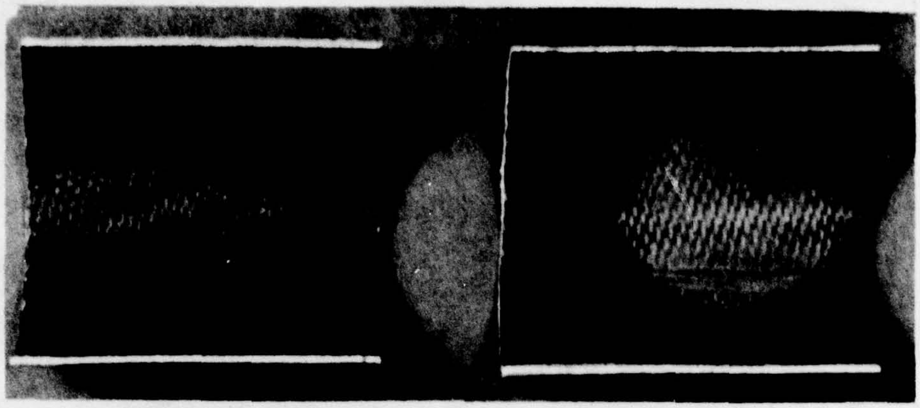
Grit Blast Test
Liner: L



Torch Test
S/N 010

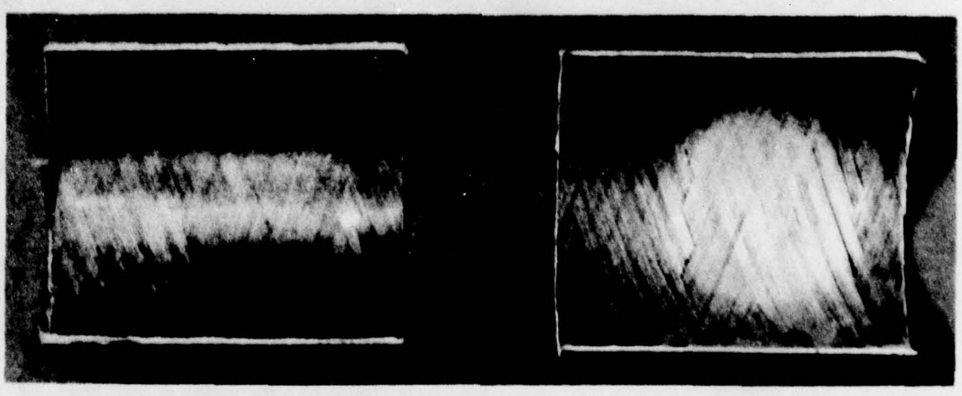
Matrix: A

Grit Blast Test
Liner: M



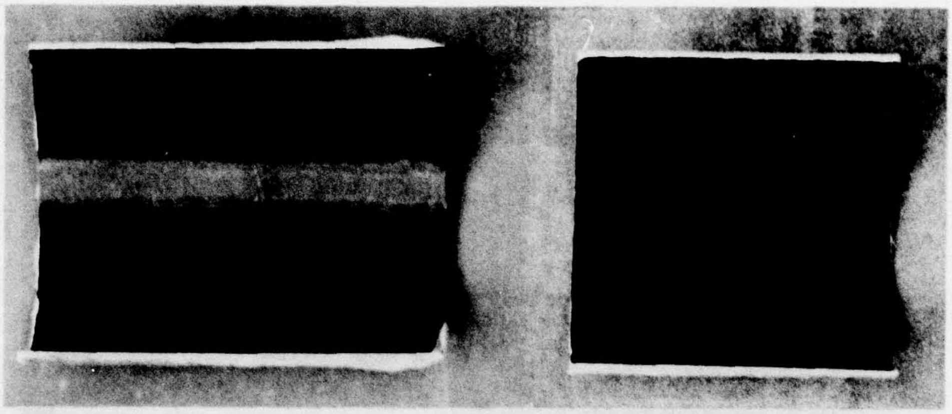
Torch Test
S/N 011 Matrix: A

Grit Blast Test
Liner: N



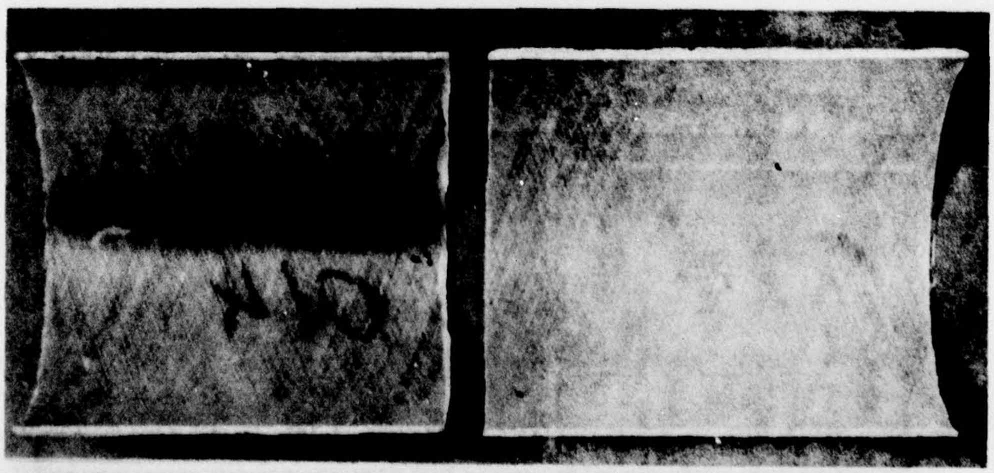
Torch Test
S/N 012 Matrix: D

Grit Blast Test
Liner: None



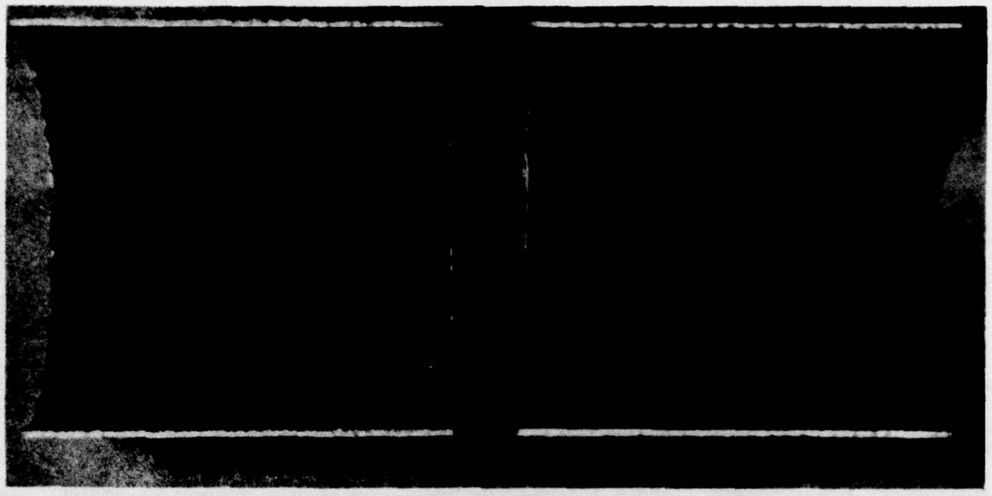
Torch Test
S/N 013 Matrix: A

Grit Blast Test
Liner: O

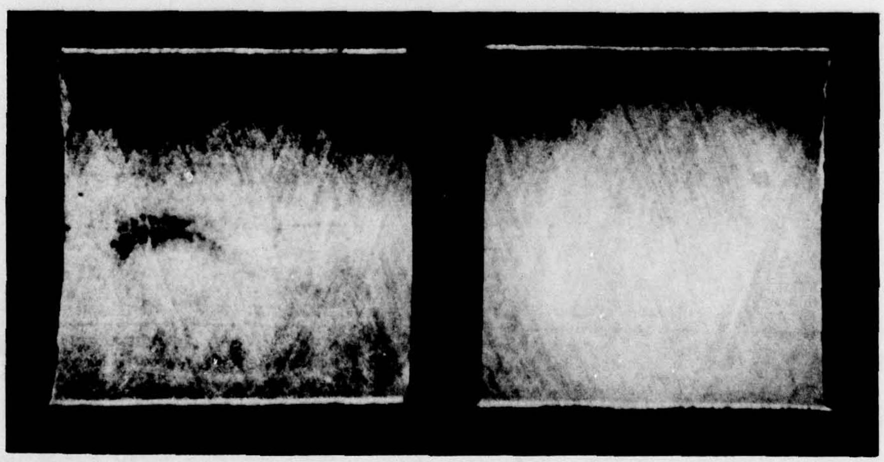


Torch Test
S/N 014 Matrix: A

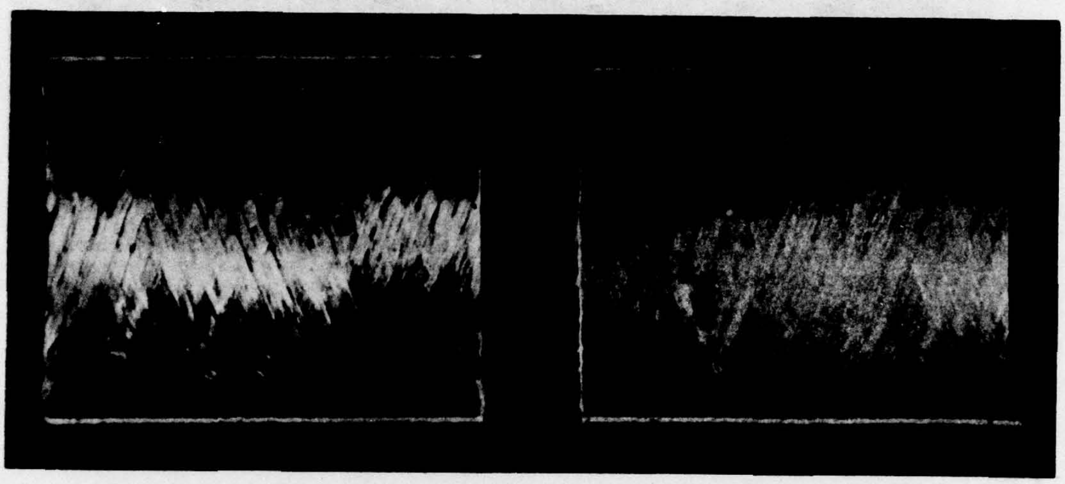
Grit Blast Test
Liner: P



Torch Test
S/N 017 Matrix: A Grit Blast Test
Liner: Q



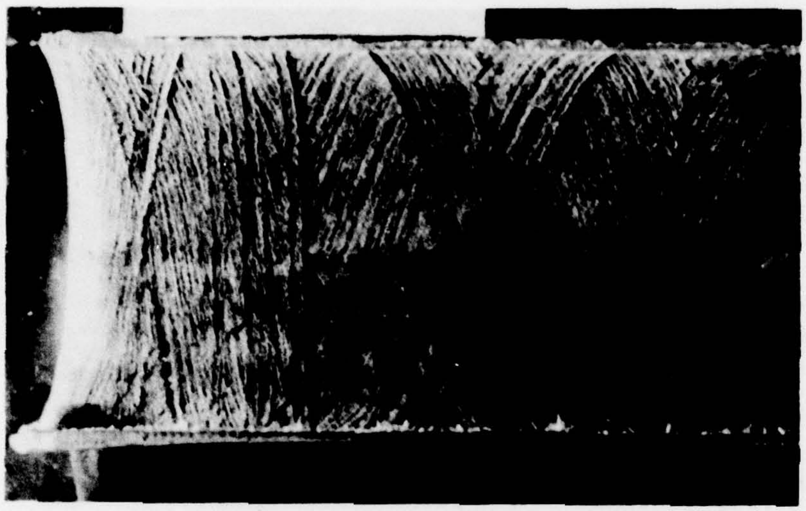
Torch Test
S/N 018 Matrix: E Grit Blast Test
Liner: R



Torch Test
S/N 019

Matrix: F

Grit Blast Test
Liner: None



Photograph of a sectioned three inch diameter launch tube which has been subjected to a single firing of a rocket similar to rocket No. 3 in Technical Requirement 6005. *The winding matrix is Epon 828/NMA with no liner.*

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